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An Apparatus for the Testing of the Dynamic Capacity of Molecular Sieve Beds

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Process Chemistry Section
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Report No 86-272-K

ABSTRACT

An apparatus was constructed and tested to investigate the effects of inlet humidity and superficial velocity on the dynamic capacity of molecular sieve beds. Two tests were conducted with superficial velocities of 47 and 49 cm/s and inlet humidities of ~950μL/L and ~900μL/L, respectively. The length of unused bed (LUB) was determined to be 3 to 5 cm when breakthrough occurred.

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Executive Summary

An Apparatus for the Testing of the Dynamic Capacity of Molecular Sieve Beds

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Earlier studies have revealed a need for the investigation of the dynamic capacity of molecular sieve beds of significant length at humidity levels under 1000μL/L, and superficial velocities above 40cm/s. To this end, an apparatus capable of testing molecular sieve beds 30cm in length was designed and constructed.

To allow the higher flow and usage rates, the building air supply was used instead of dry gas cylinders. This necessitated the inclusion of a pre-drying stage to remove the large amounts of moisture in the air supply. A flow control set-up with saturators provided the necessary control over inlet humidity to the bed. Two devices were used to measure inlet and outlet humidity levels at the bed: an EG&G chilled mirror hygrometer, and a Beckman cell.

Prior to each test, the molecular sieve towers were conditioned by drying in an oven at 210°C with a countercurrent flow of pre-purified nitrogen. Two tests were completed at superficial velocities of 47cm/s and 49cm/s, and inlet humidities of ~950μL/L and ~900μL/L, respectively. The length of unused bed (LUB) was defined

here as the length of the bed times the mass of water adsorbed after a breakthrough level of 100μL/L was reached divided by the total mass of water adsorbed to steady state. The amounts of water adsorbed were determined by integration of inlet and outlet humidities over time and the LUB's were found as 5.1cm and 3.1 cm. This was comparable to earlier tests at the University of New Brunswick, where a LUB of ~2.0cm was found in two 40cm/s tests with 1200μL/L inlet humidity. A total adsorption of 19.2% H_2O by mass was found after both tests by mass difference. The mass of the tests beds after drying in an oven was found to be constant, giving consistent initial conditions. Additionally, the constancy of flow and inlet humidity attained in the second test showed that further testing can now be conducted routinely without modification. It is recommended that this study be carried out over a range of velocities and inlet humidities to better characterize the dynamic capacity of molecular sieve beds.

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To Dr. D. Mills
Director of Research

An Apparatus for the Testing of the Dynamic Capacity of Molecular Sieve Beds

1.0 Background

Molecular sieve dryers have been in use at Ontario Hydro for over two decades. One of their main uses has been recovery of D_2O and removal of tritiated water from the atmosphere inside Nuclear Generation Facilities. This study into the effects of varying inlet humidity and flow rate was undertaken so that these dryers might be designed and utilized more efficiently. This first portion of the study consisted of the construction and testing of a bench scale apparatus capable of testing 30cm long molecular sieve towers. The results of a preliminary study at The University of New Brunswick (May 1981[1]) have indicated that further study at humidities under 1000μL/L would be valuable. Simultaneously, other effects such as velocity could also be investigated.

Molecular sieve zeolites are essentially complex aluminosilicate 'cage' structures, each with a definite pattern of SiO_4 and AlO_4 groups interspersed with cationic groups. These 'cage' cavities range in size from about 0.3nm to 1.3nm. This makes the sieves ideal for separation of molecules having dimensions of this magnitude (smaller molecules such as CO_2 up to C_{20} organic molecules). Additionally, due to the hygroscopic nature of the molecular sieve crystals, they are also ideal for water adsorption. The cavities sometimes make up over 50% (by volume) of the zeolite structure, so adsorption capacities are correspondingly large (20 to 30% by mass). The cavity structure also gives distinct advantages over less structured dessicants, such as silica and alumina. Zeolites have high capacities even in low humidity air, whereas silica and alumina have much lower capacities. Also, the adsorption capacity for

water remains high for molecular sieves above 100°C, unlike the other two adsorbents which have low capacities above 100°C.[2]

The mass transfer kinetics of molecular sieve beds are similar to those of any fixed bed, and have been described in detail elsewhere[1]. From outlet humidity measurements it is possible to construct a breakthrough curve vs time. In theory, this curve begins and ends at distinct points, but in practice it was observed that there is some leak-through prior to breakthrough, and that the outlet concentration only approaches the inlet (see 4.3 Discussion of Results). However, by defining a maximum outlet humidity, here defined as 100µL/L for 1000µL/L inlet humidity tests, a 'breakthrough' point may be determined absolutely. The length of unused bed (LUB) is determined by assuming a step-function breakthrough curve. The ratio of the water adsorbed after the breakthrough point is reached to that adsorbed at equilibrium (after a reasonably long time, or at complete breakthrough where inlet humidity equals outlet humidity) gives the ratio of the LUB to the total bed length, and thus the LUB. This has been a failing point of some previous tests, as the LUB was often too large compared to the bed length for a definitive determination (as in the UNB study [1], where LUB's of as much as 6.4cm were reported in tests with a 7.4cm long bed). This is particularly significant as the mass transfer zone (MTZ) is longer than the LUB. This MTZ moves down the bed as the sieve becomes progressively saturated and is the length of bed over which the concentration decreases from essentially the inlet value to close to zero. Finally, the percent water adsorbed may be determined either by the change in mass of the tower, or by integration of the difference in inlet and outlet humidity over time. The main purpose of this study was to find the relations of these parameters to variations in inlet humidity and superficial velocity (the speed of flow through the bed with sieve removed).

2.0 Apparatus

The apparatus used consisted of four main divisions:

- Scrubbing and Pre-Drying of Inlet Air
- Preparation of Air of Known Humidity
- The Main Test Beds
- Sampling and Humidity Determination

Each of these parts is decribed separately below. Unless stated otherwise all tubing and connectors used were stainless steel (304 or 316), either 6.35mm or 12.7mm (outer diam.). A diagram of the complete apparatus is shown in Figure 2.0.1, and specific diagrams follow the relevant pages.

2.1 Scrubbing and Pre-Drying of Inlet Air

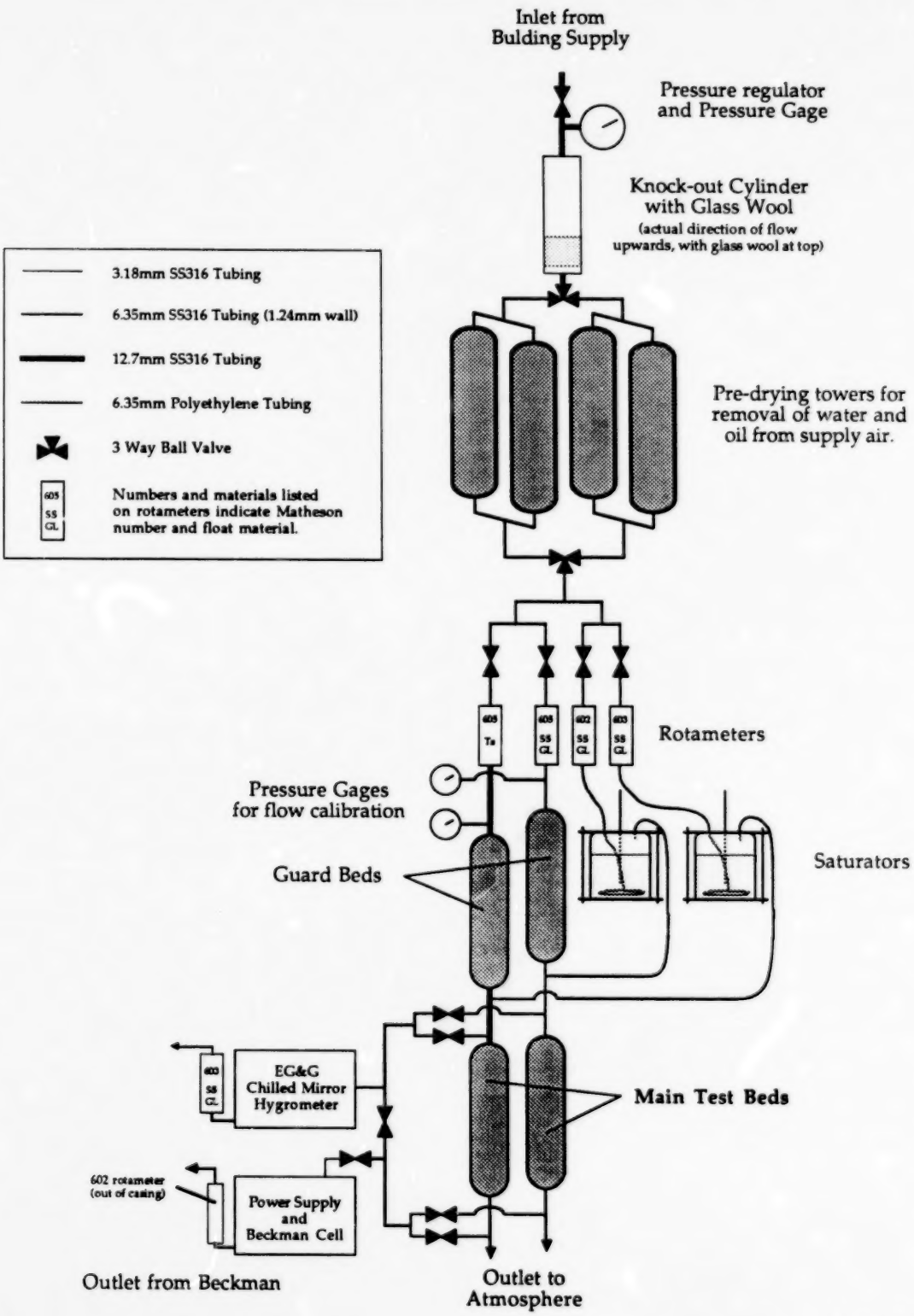
The air supply used was the building supply which typically operated at 600 to 800 kPa and ~4000 to 5000 μL/L. A pressure regulator was used to provide a steady source pressure of 570 kPa. Following the regulator was placed a tall vertical tower (5cm diam.), through which the source air flowed upwards and through about 10 cm of loose glass wool. This removed large particulate matter which appeared to be in the air supply.

To allow continuous operation, a bank-switching set-up was used for the pre-dryers. Each pre-dryer set consisted of two carbon steel pipes (8cm diameter, 30 cm length) containing molecular sieve. The length of the pre-dryers was limited to 30cm by the size of the oven used for regeneration. The air flow was downwards and glass wool was used at both ends of the towers to reduce entrainment. At the base of the tower, a brass mesh screen was also used to prevent large sieve particles from blocking the tubing. The molecular sieve used in the towers was Linde 4A, but one tower in each pair contained 3.18mm cylindrical pellets, while the other contained 4x8 mesh (2.38mm to 4.76mm) beads. This ensured similar flow through either bank of towers as each bank was of the same construction. Following pre-drying the two air streams were united.

2.2 Preparation of Air of Known Humidity

Following the pre-dryers, the dry flow proceeded through a guard bed which was necessary to protect against the small amounts of humidity which the pre-dryers allowed through after prolonged use when they began to break through. This guard bed was held at roughly a 30° angle to the horizontal with flow upwards (unlike all the other beds where flow was downwards). To

Figure 2.0.1 Overall Apparatus



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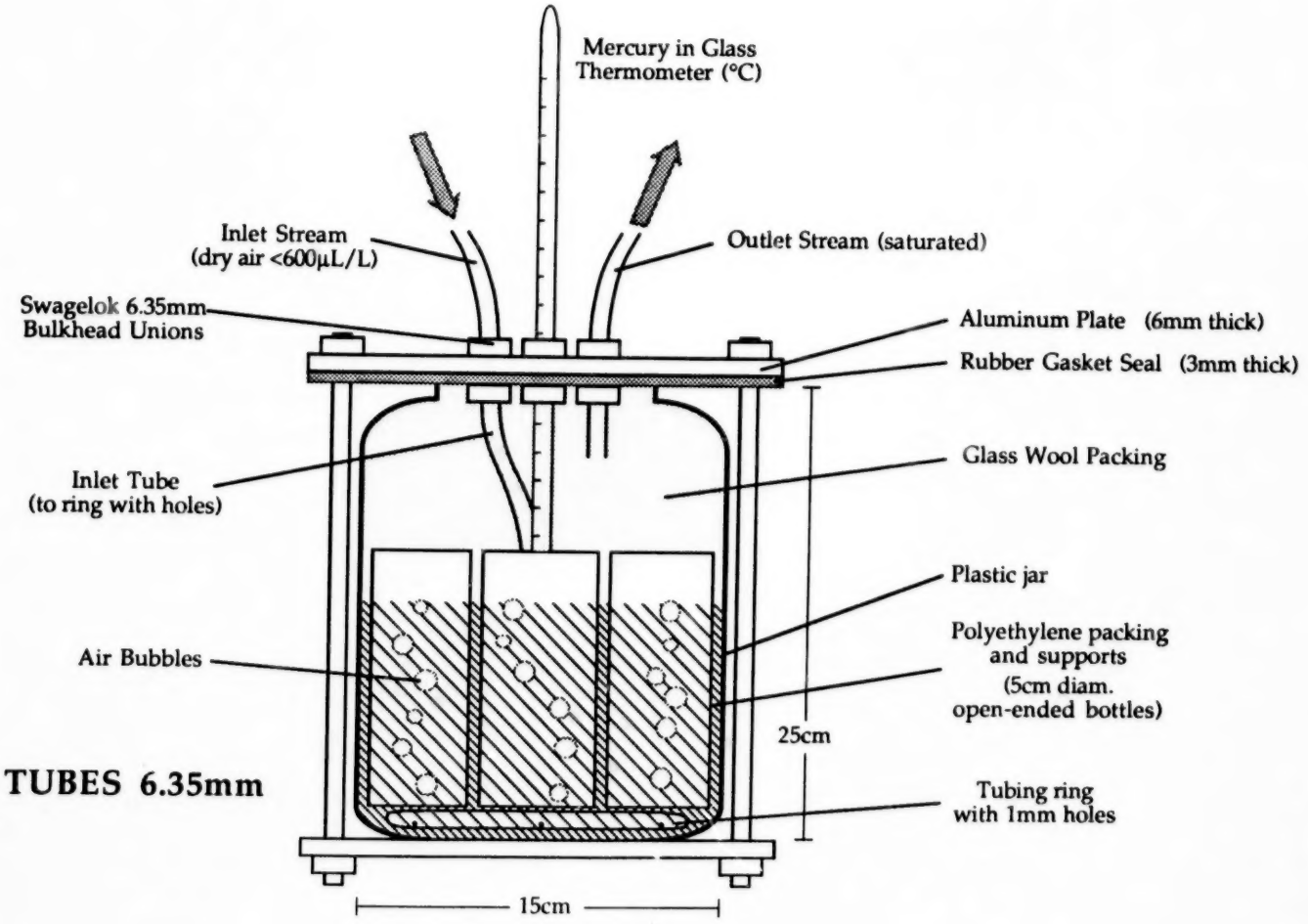
generate air of known humidity, the pre-dryed air was split into four streams, two to be saturated, and two to remain dry. By controlling the flows, air of known humidity could be produced. The flow rates were measured using rotameters for the appropriate flow range. The dry air rotameters allowed for flows of up to about 100 L/min (at NTP = 25°C, 101.3kPa), while the flow to the saturators could be as high as 4 L/min. As the saturators were not 100% effective, and the pressure within them varied greatly, the water (H_2O) content of the air produced had to be measured directly, rather than calculated from the flows. The flow was passed to and from the saturators through 6.35mm polyethylene tubing.

Each saturator (Figure 2.2.1) consisted of a water-filled 4L cylindrical plastic jar with aluminum plates at the top and bottom to hold a rubber seal snugly over the top of the jar. Through the top plate three bulkhead connectors were used to hold a thermometer and the inlet and outlet tubes. The room temperature where these experiments were conducted was held relatively constant near 25°C (±0.5°C), so that the saturators produced air of steady moisture content. All tubes connecting to the saturator were polyethylene as permeability to moisture was not a significant factor there. The inflowing air was passed into a perforated ring of tubing at the base of the jar. In each ring were four to eight holes with diameters of approximately 1mm. This arrangement was found to give reasonable pressure drops with the desired flows, while producing small enough bubbles for good humidification. Each saturator was packed with open ended polyethylene bottles with the bottoms removed, and placed vertically in a hexagonal arrangement (6 bottles + 1 in the middle). The main purpose of these was to support the glass wool at the top of the jar, but the packing also helped keep the bubble streams separate at higher flow rates. The glass wool served to prevent entrainment, diffuse the flow, and further saturate the air stream. The thermometer placed in the central bulkhead was a mercury thermometer with a -30°C to +50°C scale and a precision of about ±0.02°C.

After saturation the flow from the saturators was mixed with the dry flow, producing air of the desired humidity. Prior to the test bed, an outlet valve was connected to allow measurement of inlet humidity. A similar connection was made just prior to the outlet vent to atmosphere.

Figure 2.2.1 Saturator



2.3 The Main Test Beds

The test bed itself (Figure 2.3.1) was contained in a 30cm long, 5.4cm internal diameter, Schedule 10, SS316 tube with butt welded caps on either end. To facilitate changing of the sieve in the test bed (to allow testing of various sieves), the tubing was expanded to 19.1mm at the inlet. This also gave more uniform flow at the inlet. The flow through the test beds was downwards, as the high velocities used were near those at which entrainment would occur with upflow. Inside the test container was a bed about 30cm in length with glass wool at either end. At the base, fine stainless steel mesh was used to retain the sieve. The bed length of 30cm was determined by measurement of the sieve volume loaded, assuming a constant internal diameter. The volume in turn was measured by weighing 500mL of sieve (moisture content as delivered) which had been packed by shaking. The actual mass and volume used were then calculated proportionately. For the tests described here, 428.4g of 3.18mm 13X Linde molecular sieve pellets (corresponding to 687mL, or a 30cm main test bed length) was placed in each of the two towers used. Four grams of mass were lost in drying, so that the dry mass of sieve was taken to be 424.4g (±0.5g).

2.4 Sampling and Humidity Determination

Sample valves were connected to the inlet and outlet of each bed. Two devices were used to measure the humidity of the outlet stream, an EG&G chilled mirror hygrometer, and a Beckman cell. The Beckman cell (Figure 2.4.1) was connected to a 15V power supply at one connector and to two 300Ω resistors in series to ground at the other. The output signal was taken between the resistors, giving a maximum output of 7.5V. The flow through the Beckman cell was maintained at 104 mL/min (at 25°C and atmospheric pressure, though inlet flow sometimes varied as much as ±5 mL/min at 'steady' state). The signal from either device was then passed to a single-pen Philips PM8251 chart recorder for continuous data charting. When both devices were used simultaneously, the inlet humidity, measured with the EG&G only, was recorded on a second chart recorder.

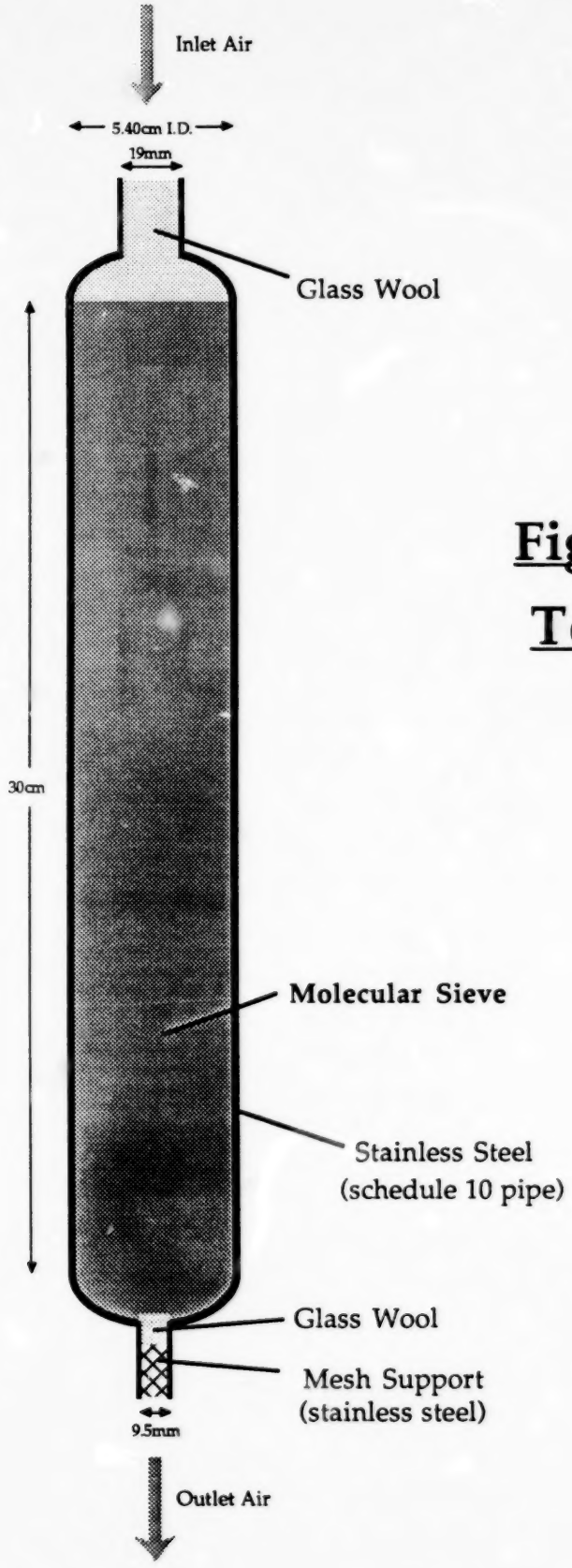
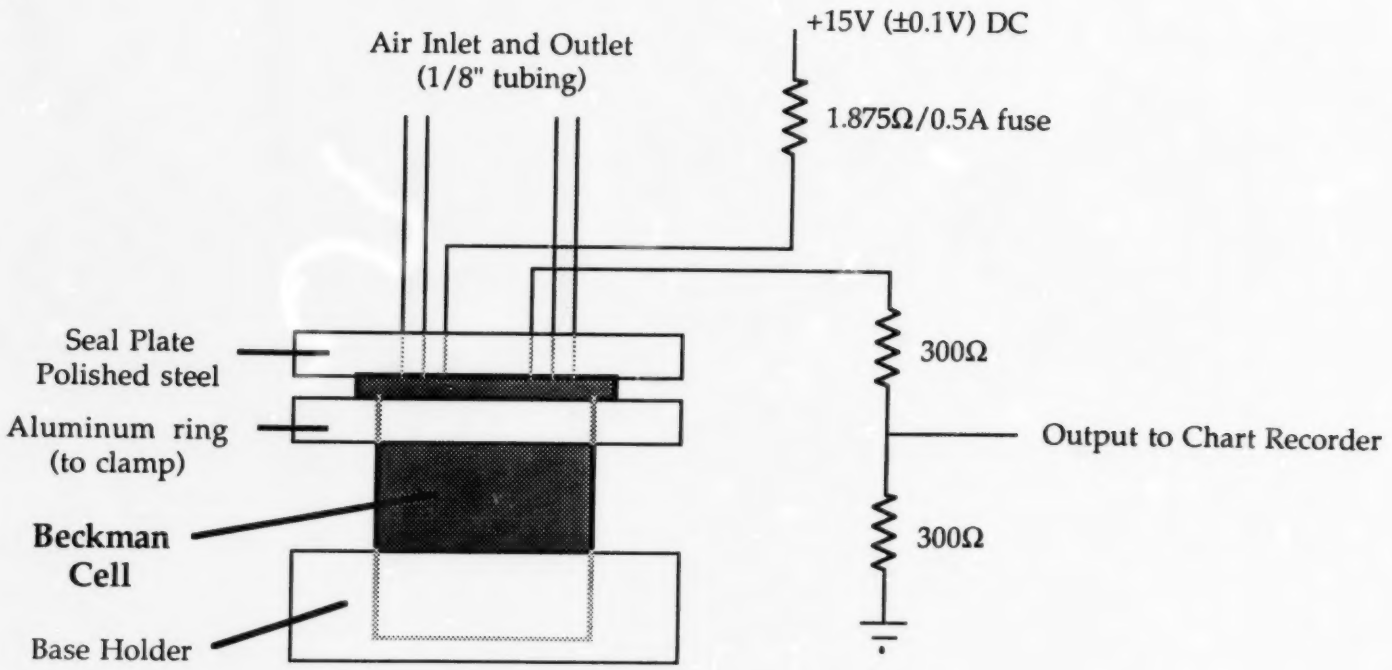


Figure 2.3.1

Test Beds

(half scale)

Figure 2.4.1 Beckman Cell and Power Circuit



3.0 Experimental Procedure

3.1 Drying of Molecular Sieve Beds

Before each test the pre-dryers, guard bed, and main test tower were dryed to provide proper initial conditions. All drying was done in an oven at 210°C (±10°C) and all dryers were dryed counter-currently, with pre-purified nitrogen flowing in a direction opposite to that used during the actual experiment. The times for drying given are timed from turning on of the oven. It was noted that the oven took about two hours for the oven to reach 200°C, but the dry flow would probably have removed much water even at room temperature due to equilibrium desorption. The pre-dryers were generally dryed with a flow of ~100 mL/min for eighteen to twenty-four hours, though equivalent dryings (such as 300mL/min for seven hours) were often made. This was observed to provide twelve hours of <10μL/L exit humidity at a flow of about 60 L/min, and six more hours with under 600μL/L exit humidity. The guard bed was dryed under equivalent conditions, but typically for shorter periods (~400mL/min for six hours). This provided protection against breakthrough during those six hours when the pre-dryers were breaking through. The test towers were dryed under the more exact conditions of 250 mL/min (±20 mL/min) for eighteen hours. Following drying, all towers were sealed to ambient air, and cooled for about two hours. The final cooling (~40°C to 25°C) was often accelerated when necessary by water cooling of the outer casing. To test the dryness of all towers, an air flow was passed through them, and the outlet humidity measured. A dew point on the EG&G hygrometer of less than -50°C was used as a limit of acceptability. If a tower read above that humidity level, then it was dryed again. In the case of the test towers, the tower would be run to breakthrough and then dryed again to give the required initial conditions.

3.2 Main Testing Procedure

To allow constant flow, the pressure regulator at the supply air source was set to 570 kPa (65psig). The dry and humid flows were then slowly brought up to

roughly the desired level, so as to prevent a sudden rush of humid air through the test tower. This was easily done in under a minute. The humidity and flows could then be fine-tuned as desired. The determination of these conditions was generally done with the test bed in place prior to drying it down. The flows and pressures, where measured, were recorded (during the day) at intervals of about two hours to assure steady conditions, or correct for serious deviations. Generally the inlet humidity was monitored for up to an hour after start-up, to be assured of stable conditions. The outlet humidity was then measured to completion of breakthrough. The test was carried through until the outlet humidity was either very steady near the inlet level or longer if time permitted. After each test, all beds were quickly sealed against ambient and building supply air, as these might have caused damage and/or errors in later tests. When the Beckman cell was used initially for outlet humidity measurement, it was found necessary to switch over to the EG&G hygrometer above concentrations of 200μL/L. The Beckman was found to give neither consistent nor accurate readings for more humid air after protracted periods of drying. In practice, the Beckman was typically used only up to a water concentration of about 150μL/L.

3.3 Pre-Dryer Bank Switching

Originally it had been hoped that the building supply air would be drier than it proved to be, and that the pre-dryers would suffice for several days, but it was soon obvious that a guard bed was necessary for even overnight continuity. During those tests which lasted longer than 18 hours it was necessary to bank-switch the pre-dryers. One set would be used overnight for 16-19 hours (thus the need for the guard bed) and the other for the remainder of the day. When a set of pre-dryers was not being used it was dried in the oven (both towers at once) until two hours before use. Under these conditions, the maximum average humidity level at the inlet to the guard bed would be less than 100μL/L. Therefore, as the test bed was of similar construction, with inlet humidities of about 1000μL/L, breakthrough of the guard bed could not occur during the test.

4.0 Results and Discussion

A total of six tests were conducted: two preliminary tests, and tests #1, #2-1, #2-2, and #2-3. The results discussed have been calculated from the data presented in Appendices A4.2.1 and A4.2.2. It should be noted that the two tests presented (tests #1 and #2-3) were those which were carried to completion. Tests #2-1 and #2-2 were terminated due to equipment failure (leaking saturator, and oven electrical failure). All tests discussed were carried out using the high flow path (flows were split, as shown in Figure 2.0.1, to allow simultaneous testing of two beds) which included the Matheson 605 rotameter with a tantalum float, the 603 rotameter for saturating the flow, and 12.7mm stainless steel tubing for most of the dry air lines (see 2.0 Apparatus).

4.1 Calculations

The main calculation for each test was that of the length of unused bed (LUB). As stated previously, breakthrough was taken to occur at an exit humidity level of 100μL/L. As the rise in humidity generally was sharp (Figures 4.2.1 and 4.22), this humidity level was roughly equivalent to any under about 250μL/L, allowing comparison with other studies where the breakthrough humidity was under 250μL/L. Moisture adsorbed was taken in terms of the difference between inlet and outlet concentrations, as the flow rates were nearly constant over each test. The adsorption was then integrated vs time in two parts: prior to breakthrough, and from breakthrough to steady state. To determine the LUB, the ratio of the post-breakthrough value to the total was multiplied by the length of the bed (30cm).

The total flow through the system was needed to determine total adsorption from the humidity readings, and also to find the superficial velocity. Calibration curves for the four main rotameters were generated prior to the experiment, and fit to polynomials (see Appendices A4.1.1 to A4.17). The rotameters following the Beckman and EG&G hygrometers were calibrated against the other rotameters for the relevant values (104mL/min for the Beckman and 660mL/min for the EG&G). Because of the pressure related behaviour of the rotameters, it was necessary to adjust the values for pressure

as follows [3]:

$$\text{Flow}_{actual} = \text{Flow}_{calibration} * \sqrt{P}_{rotameter} / \sqrt{P}_{calibration}$$

where Flow_{actual} was the actual flow in the system at the calibration pressure, which in this case was atmospheric pressure (101kPa). Thus, from the rotameter and pressure readings, the flows could be readily determined. The total flow through the test tower was calculated as the sum of the dry and saturated flows minus (when the inlet was measured) the inlet sample flow to the EG&G hygrometer.

4.2 Results

Of the several tests started, only two were run to completion: tests #1 and #2-3. The superficial velocities in these tests were 47 cm/s and 49 cm/s, while the inlet humidities were ~950μL/L and ~900μL/L, respectively. However, in test #1, as inlet humidity was only measured at the start and end of the test, inlet humidity was not sufficiently well determined. Graphs of the humidity data collected are shown in Figures 4.2.1 and 4.2.2, for tests #1 and #2-3, respectively.

The mass of the test bed used in both successful tests was relatively constant after drying (prior to testing). In tests #1, #2-2, and #2-3, the main test tower had a mass of 2300.0g, 2300.0g, and 2299.5g (including the sieve, which had a dry mass of 424.4g). Following testing the bed also appeared to have constant mass (and thus adsorption) – for both tests #1 and #2-3 the tower had a final mass of 2381.0g.

The total adsorption by mass was nearly the same in both tests (81g), a total adsorption of 19.2g $H_20/100g$ sieve. When determined from integration, the figures were somewhat different. In test #1, integration of the graph to the end of the test times flow yielded a total adsorption of 95g while integration only to steady state gave an adsorption amount of 83g. In test #2-3, integration to the end of the test gave a total adsorption of 48g (62g when outlet humidities above the inlet were ignored).

Figure 4.2.1 Inlet and Outlet Concentrations vs Time for Test #1

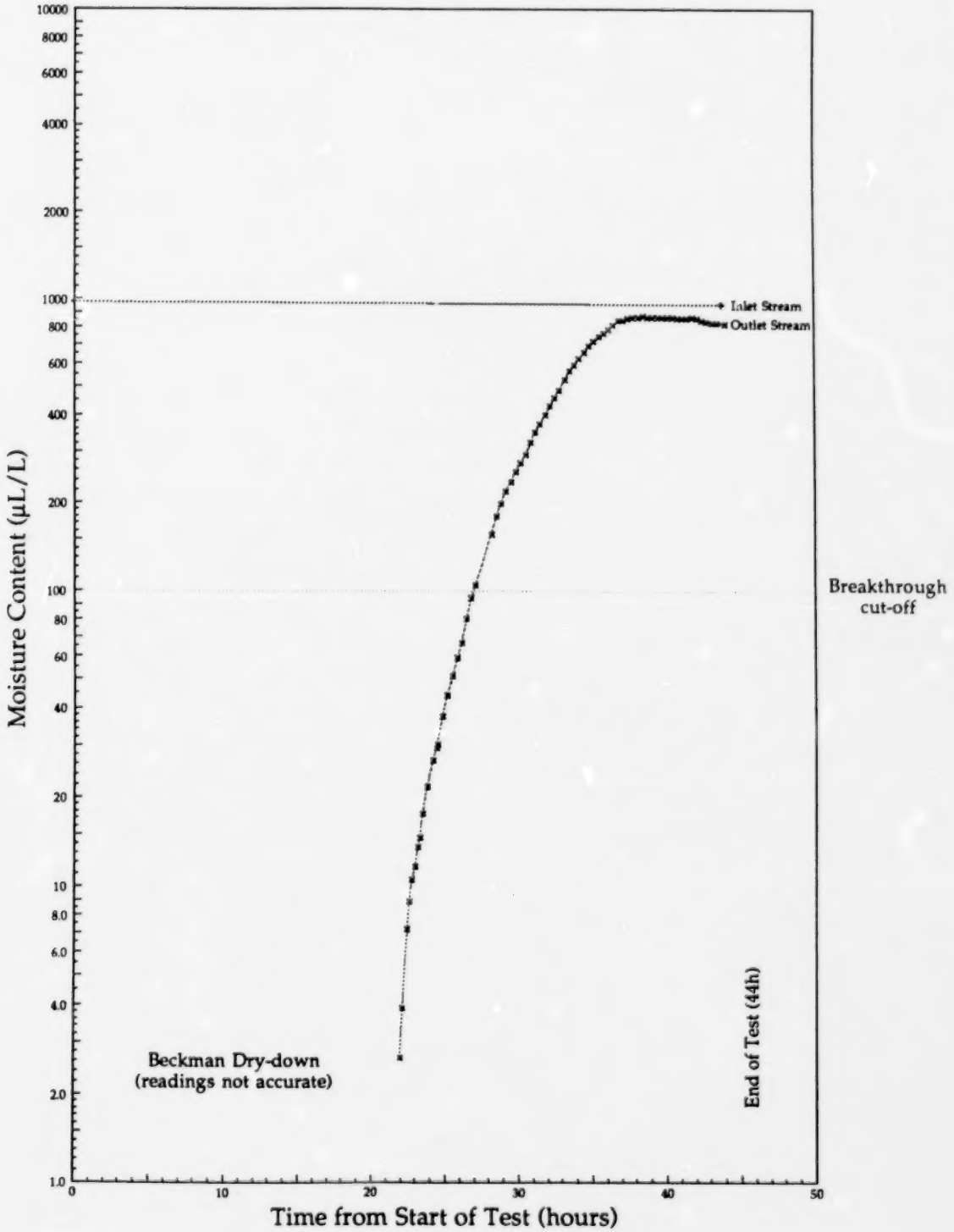
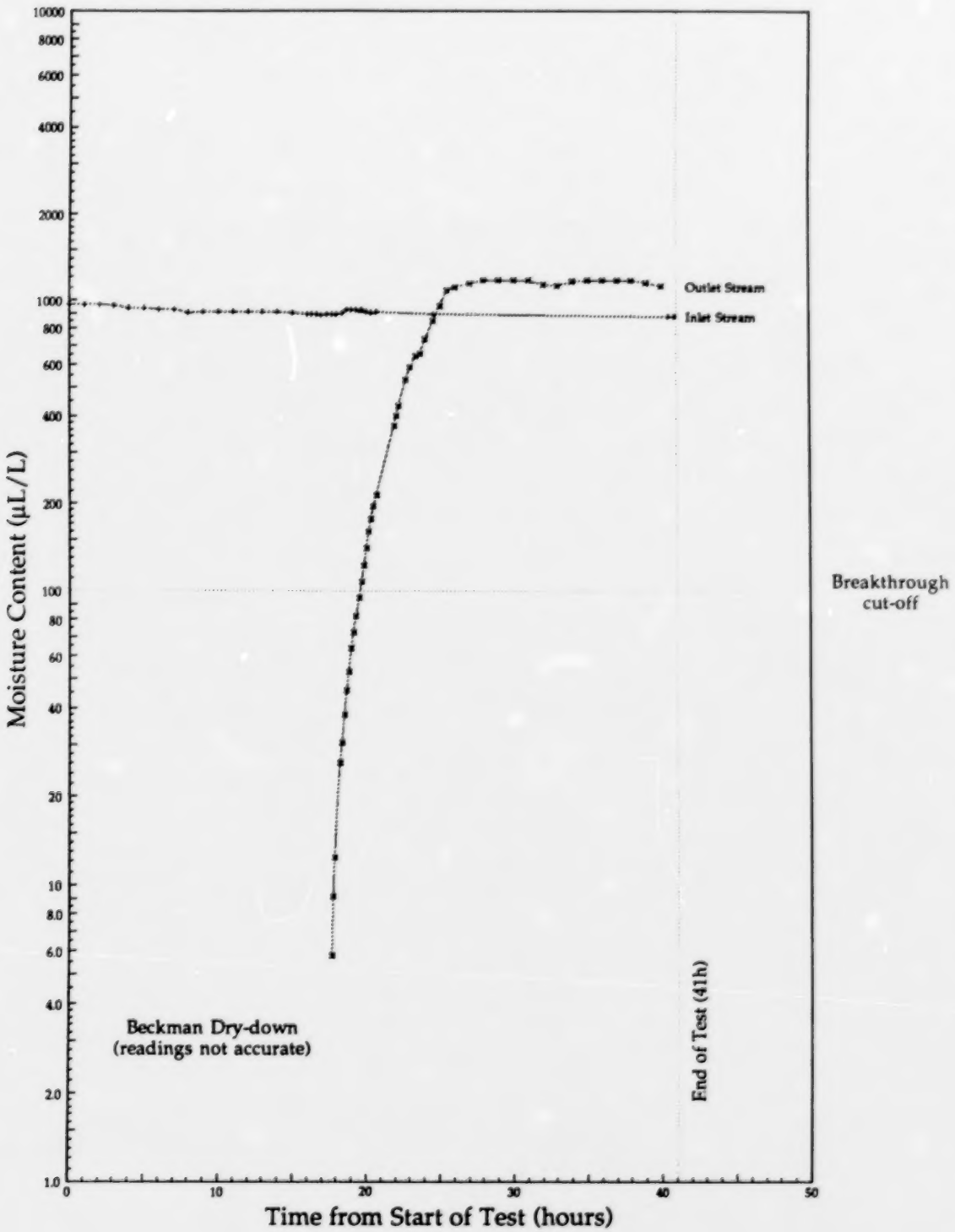


Figure 4.2.2 Inlet and Outlet Concentrations vs Time for Test #2-3



As might be expected, the LUB's from these tests were similarly different. In test #1 the LUB was determined as 5.1cm, and in test #2-3 as 3.1cm. In both cases the integration for LUB was carried only to where the outlet humidity leveled off and steady state appeared to have been reached (to 36:46h in test #1 and to 26:00h in test #2-3). In test #1, carrying on to the end of the test gave an LUB of 5.7cm, and for test #2-3 this gave a negative value of approx. -3cm. An alternate method of determining the LUB was also investigated. The integration method was used to find adsorption prior to breakthrough from the inlet and outlet humidity data. The total mass adsorbed was found by mass difference from the start to the end of the test (~81g in both cases). This gave an LUB of 3.1cm for test #1, and 9.5cm for test #2-3. These figures were not reasonable as the breakthrough curve from test #2-3 showed a much sharper rise in outlet humidity, and therefore should have had a shorter LUB.

4.3 Discussion of Results

As only two tests were completed, only general remarks and comparisons amy be made. Further, these two tests do not agree well at all, despite similar conditions. This was possibly caused by variable inlet conditions for test #1, which were ruled out in test #2 as inlet humidity was monitored throughout the test. The constancy of mass noted for the test tower suggests that the drying procedure employed gave good initial conditions. The fact that the mass was the same at the end of both test runs may merely be chance due to the small number of tests. However, conditions during the tests were not exactly the same, so the mass similarity could be due to adsorption of some substance other than water (the 13X sieve used adsorbs many substances).

The difference between outlet and inlet humidities in test #1 would follow from variable inlet conditions. In test #2-3, though, there was no reason to suspect poor inlet conditions. The rise of outlet humidity above inlet humidity was apparently not noted in the preliminary study conducted, but the charts in that report did not generally show steady state conditions. Clearly further study is required with complete (inlet and outlet) data in the steady state range to determine whether this rise above inlet humidity occurred through an error or if it is a common phenomenon. The sharp rise in the

breakthrough curve of test #2-3 suggests fair utilization of the bed, as illustrated by the LUB of only 3.1cm. The negative value obtained by continuing to the end of the test (-3cm) suggests that if such behaviour is common, the method of calculating the LUB by integration of humidity over time may not be appropriate.

In the preliminary study[1], testing with a shorter bed under conditions similar to those used here (1200μL/L inlet concentration, 150μL/L breakthrough, and 40cm/s superficial velocity), Linde 13X sieve pellets gave a LUB of about 2cm which is not far removed from the result of test #2-3. However, in those tests a much smaller bed (3.8cm diam., 7.4cm length) was used, and its behaviour would clearly have been less similar to larger beds than the test bed used here (5.4cm diam., 30cm length). For larger superficial velocities and less adsorbent types of sieve the LUB increases, so that a larger size for the test bed will be even more significant.

5.0 Conclusions and Recommendations

1. The apparatus as constructed is capable of providing a steady flow of air with a steady concentration of water (in the current temperature controlled environment). This makes it suitable for further testing at various humidity levels, velocities, and with other types of molecular sieve.

2. Unusual behaviour was noted near the end of both successful tests where inlet humidity did not match outlet humidity at what appeared to be steady state. Further study is recommended, especially to steady state.

3. The Beckman cell as used here was not efficient over a wide enough range (only up to ~200μL/L), and needed to be recharged regularly to assure good operation. The experiment will give more complete results with two dew point measurement devices with a range minimally from -50°C to -10°C measuring both inlet and outlet concentrations simultaneously.

4. Addition of an in-line dehumidification unit directly following the air supply would reduce the load on the pre-dryers. They would last longer, allowing more continuous operation, which would allow tests at lower velocities and humidity level

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2. BDH Chemicals Ltd., **Union Carbide Molecular Sieves**, third edition.

3. Coulson, J.M., Richardson, J.F., **Chemical Engineering**, Pergamon Press, Somerset, second edition, 1966.

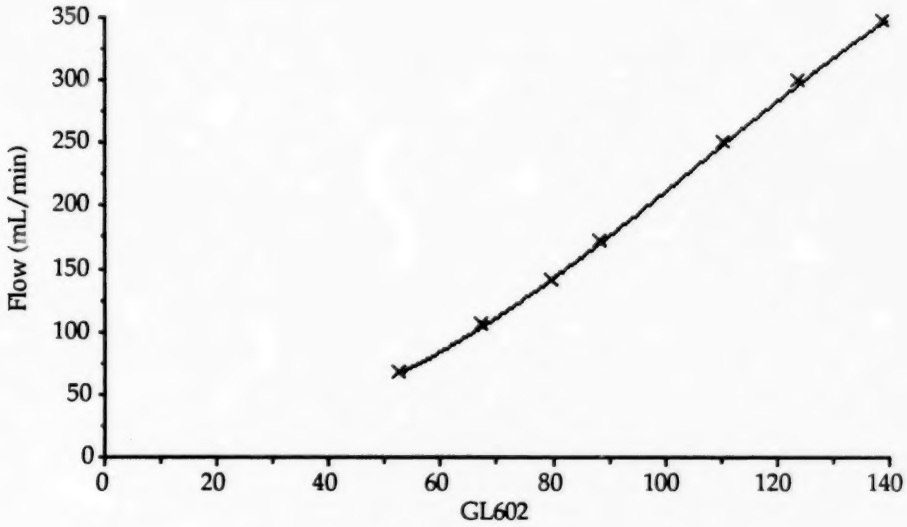
APPENDIX

Calibration data and data obtained in Tests #1 and #2-3 are presented in this appendix.

Note on A4.1.1 to A4.1.7: The values on the x-axis are the rotameter readings in mm. Readings above 140mm were found to be inconsistent

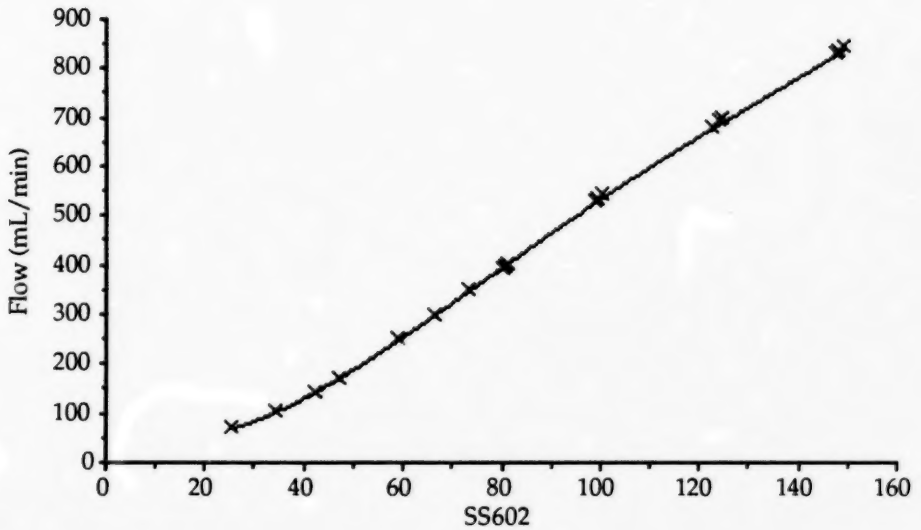
A4.1.1 Calibration curve for Matheson 602 rotameter Glass float (with stainless steel float)

(Flow = $-7.155 \cdot 10^{-7}x^4 + 1.0245 \cdot 10^{-4}x^3 + 0.0169869x^2 + 0.0156971x + 8.74557$)



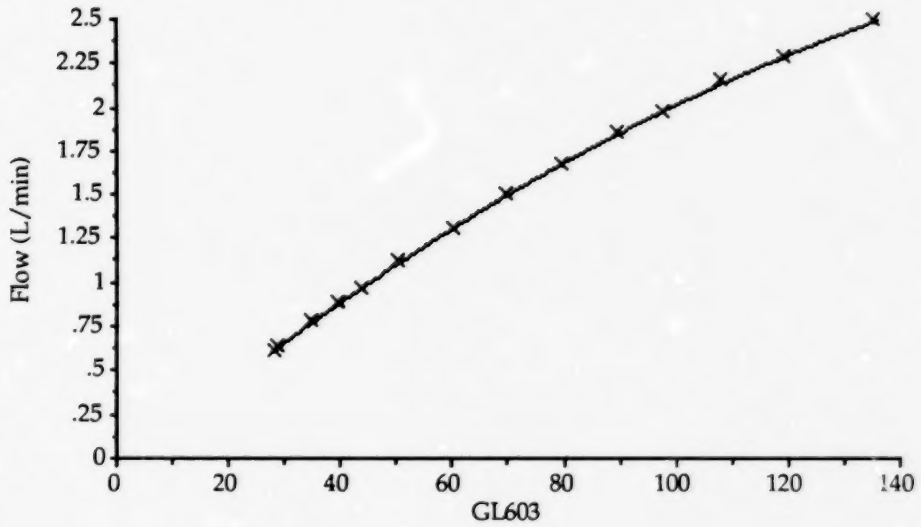
A4.1.2 Calibration curve for Matheson 602 rotameter Stainless Steel float (with glass float)

(Flow = $2.70945 \cdot 10^{-6}x^4 - 1.15168 \cdot 10^{-3}x^3 + 0.169152x^2 - 3.40014x + 61.2110$)



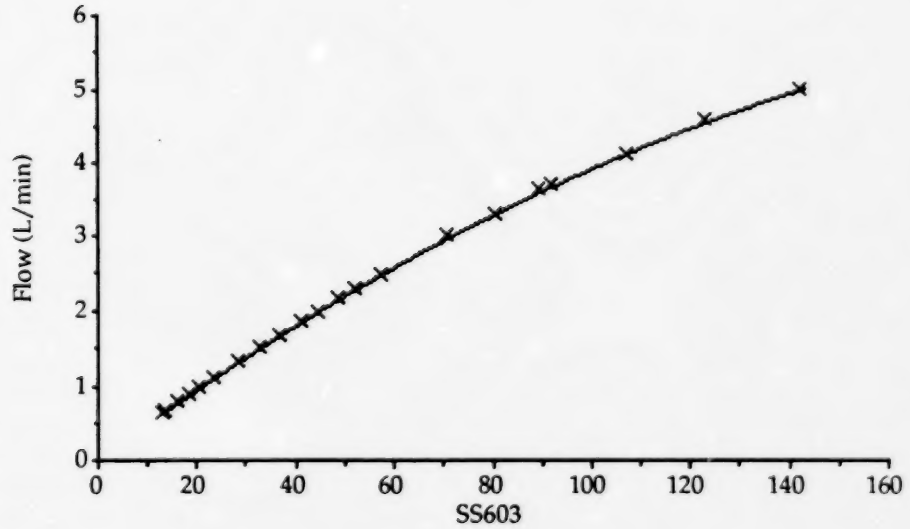
A4.1.3 Calibration curve for Matheson 603 rotameter Glass float (with stainless steel float)

(Flow = - $5.6074 \cdot 10^{-5} x^2$ + 0.0266260x - 0.088480)



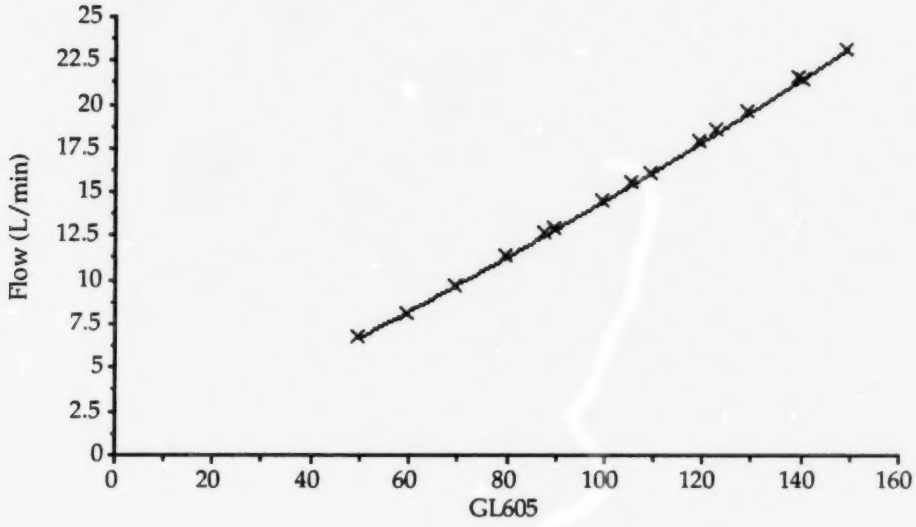
A4.1.4 Calibration curve for Matheson 603 rotameter Stainless Steel float (with glass float)

(Flow = - $9.8297 \cdot 10^{-5} x^2$ + 0.0492035x - 0.0165953)



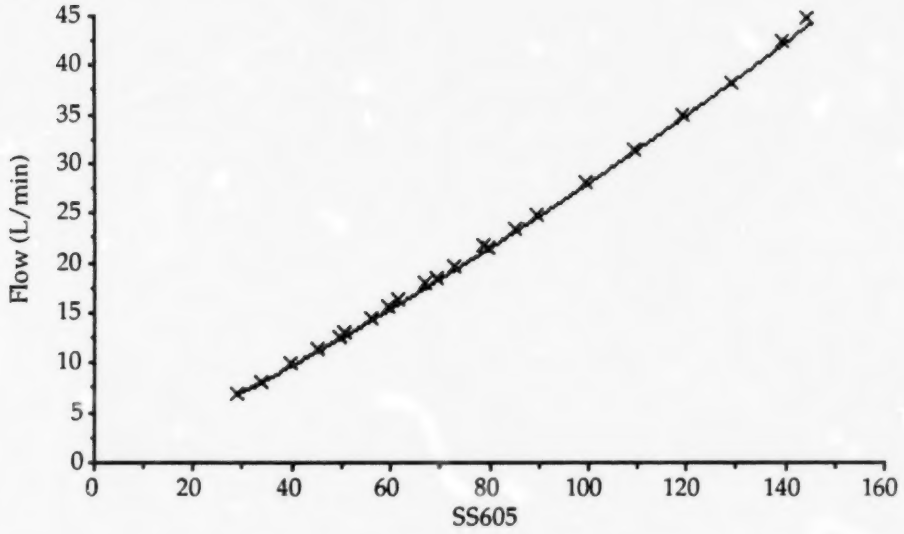
A4.1.5 Calibration curve for Matheson 605 rotameter Glass float (with stainless steel float)

(Flow = $1.90529 \cdot 10^{-4}x^2 + 0.127086x - 0.0911864$)



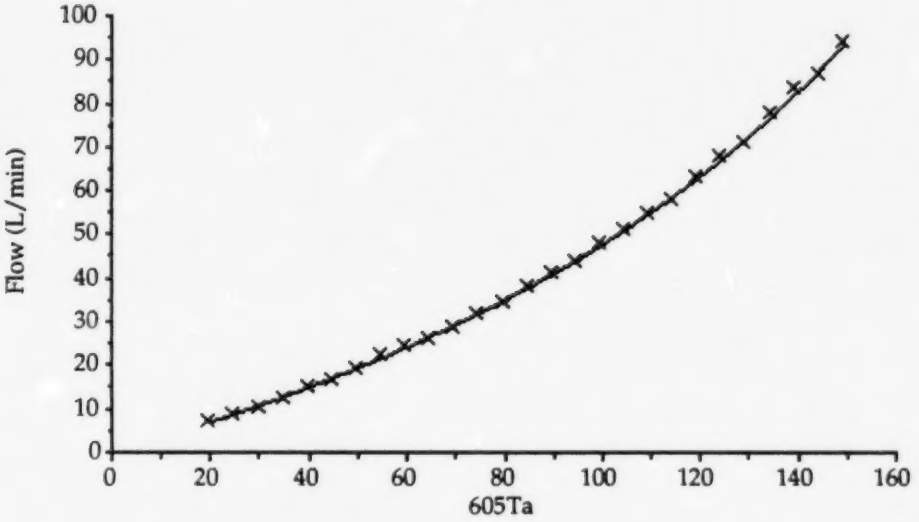
A4.1.6 Calibration curve for Matheson 605 rotameter Stainless Steel float (with glass float)

(Flow = $5.3580 \cdot 10^{-4}x^2 + 0.229887x - 0.238067$)



A4.1.7 Calibration curve for Matheson 605 rotameter with Ta float

(Flow = $6.31812 \cdot 10^{-8}x^4 + 7.2482 \cdot 10^{-6}x^3 + 1.83000 \cdot 10^{-3}x^2 + 0.301472x + 0.178551$)



A4.2.1 Results from Test #1

Initial Mass of Sieve Tower:	2300.0g
Mass After Test:	2381.0g
Total Flow (at 101kPa):	65.2 L/min
Superficial Velocity (at 101kPa):	47 cm/s

	Time from Start (hr : min)	Inlet (µL/L)	Outlet (µL/L)
Start of Test #1	0:00	973	—
	21:57	—	2.63
	22:06	—	3.90
	22:26	—	7.16
	22:38	—	8.87
	22:46	—	10.6
	22:56	—	11.7
	23:06	—	13.6
	23:13	—	14.6
	23:26	—	17.6
	23:46	—	21.6
	24:06	—	26.6
	24:21	—	29.3
	24:26	—	30.3
	24:46	—	37.4
	25:06	—	44.0
	25:26	—	51.3
	25:46	—	59.5
	26:06	—	66.5
	26:26	—	80.6
	26:44	—	94.5
	27:00	—	105
	28:06	—	156
	28:26	—	180
	28:46	—	198
	29:06	—	219
	29:26	—	236
	29:46	—	254
	30:06	—	274
	30:26	—	292
	30:46	—	321
	31:06	—	350

	31:26	—	372
	31:46	—	400
	32:06	—	430
	32:26	—	457
	32:46	—	486
	33:06	—	527
	33:26	—	566
	33:46	—	595
	34:06	—	626
	34:26	—	658
	34:46	—	692
	35:06	—	720
	35:26	—	741
	35:46	—	763
	36:06	—	786
	36:26	—	810
	36:46	—	842
	37:06	—	842
	37:26	—	858
	37:46	—	867
	38:06	—	867
	38:26	—	875
	38:46	—	867
	39:06	—	867
	39:26	—	867
	39:46	—	867
	40:06	—	867
	40:26	—	867
	40:46	—	858
	41:06	—	858
	41:26	—	858
	41:46	—	867
	42:06	—	858
	42:26	—	842
	42:46	—	834
	43:06	—	826
	43:26	—	826
	43:46	954	—
End of Test #1	44:00	—	818

A4.2.2 Results from Test #2-3

Initial Mass of Sieve Tower:	2299.5g
Mass After Test:	2381.0g
Flow (at 101kPa):	67.9 L/min
Superficial Velocity (at 101kPa):	49 cm/s

	Time from Start (hr : min)	Inlet (μL/L)	Outlet (μL/L)
Start of Test #2-3	0:00	964	—
	1:00	964	—
	2:00	964	—
	3:00	953	—
	4:00	937	—
	5:00	937	—
	6:00	928	—
	7:00	928	—
	8:00	909	—
	9:00	918	—
	10:00	918	—
	11:00	918	—
	12:00	918	—
	13:00	918	—
	14:00	918	—
	15:00	909	—
	16:00	901	—
	16:20	901	—
	16:40	901	—
	17:00	892	—
	17:20	901	—
	17:30	901	—
	17:34	901	—
	17:40	901	5.77
	17:44	892	9.18
	17:49	892	12.4
	18:00	892	—
	18:10	901	—
	18:12	—	26.0
	18:20	909	30.6
	18:30	928	38.0
	18:40	928	45.7

	18:49	937	52.9
	19:00	928	63.5
	19:10	928	72.6
	19:20	928	81.8
	19:30	918	94.6
	19:40	928	107
	19:50	918	122
	20:00	918	140
	20:10	918	159
	20:20	909	176
	20:30	909	194
	20:40	918	213
	21:50	—	369
	22:00	—	400
	22:10	—	434
	22:20	—	467
	22:40	—	533
	23:00	—	589
	23:20	—	646
	23:40	—	658
	24:00	—	734
	24:30	901	850
	25:00	—	953
	25:30	—	1082
	26:00	—	1113
	27:00	—	1145
	28:00	—	1178
	29:00	—	1178
	30:00	—	1178
	31:00	—	1178
	32:00	—	1134
	33:00	—	1124
	34:00	—	1167
	35:00	—	1178
	36:00	—	1178
	37:00	—	1178
	38:00	—	1178
	39:00	—	1155
	40:00	—	1124
	40:30	884	—
	40:40	884	—
	40:50	884	—
End of Test #2-3	41:00	—	—

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